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**Citation for published version:**

Donoghue, S, Furley, PA, Stuart, N, Haggis, R, Trevaskis, A, Lopez, G & Aitkenhead, M (ed.) 2019, 'The nature and spatial variability of lowland savanna soils: Improving the resolution of soil properties to support land management policy', *Soil Use and Management*. <https://doi.org/10.1111/sum.12513>

**Digital Object Identifier (DOI):**

[10.1111/sum.12513](https://doi.org/10.1111/sum.12513)

**Link:**

[Link to publication record in Edinburgh Research Explorer](#)

**Document Version:**

Peer reviewed version

**Published In:**

Soil Use and Management

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**The nature and spatial variability of lowland savanna soils: improving the resolution of soil properties to support land management policy**

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**Running title:** Spatial variability of lowland savanna soils

## 14    **Abstract**

15    A fresh approach is presented to address the increasingly urgent need for alternative land management  
16    strategies in savannas. We illustrate how fine-scale information of soil characteristics can be used to  
17    enable a more precise delimitation of sites suitable for different forms of land stewardship, including  
18    agro-pastoral activities, forestry, biodiversity and tourism. By collating data from previous soil  
19    surveys, and augmenting this with targeted new surveys, we produce the first national data set of soil  
20    properties for the lowland savannas of Belize. Most of these soils are typical of savanna soils  
21    worldwide, i.e. acidic (mean surface pH = 5.7), nutrient-poor (mean surface TEB = 3.4 cmol/kg), and  
22    coarse textured (mean surface clay = 13.0%). Nevertheless, there is a marked spatial variability across  
23    the country in these soil properties. Some soils exhibit unusually high subsurface clay fractions (max  
24    = 73%), whilst other sites have exceptionally high pH in lower horizons (max = 8.4). Cluster analysis  
25    is used to group sites with similar soil properties. Across 79 sites there is a clear division between  
26    soils with high clay percentages and those with coarser textures. These are sub-divided into five  
27    groups based on further differences in parent material, chemical properties, and site characteristics.  
28    Mapping the locations of these groups enables more specific land use recommendations to be made.  
29    This ability to make targeted land use recommendations from fine scale soil information represents  
30    an advance over the previous national land use policy, where all savanna lands were considered  
31    unsuitable for any form of agriculture. This approach could be applied to marginal savannas  
32    worldwide.

33    Key words: savanna soils, cluster analysis, land management, Belize

## 34    **1. Introduction**

35    Throughout the world inappropriate management practises in savannas have led to soil degradation,  
36    with a major loss of organic matter (OM) that has contributed to global carbon emissions (Grace *et*  
37    *al.*, 2006). These impacts are well documented in savanna regions such as the Brazilian *cerrados*,  
38    where degradation is predominantly due to clearance for large-scale agriculture (Klink and Machado,

1995). However, as a result of increasing population pressures, other savanna areas within the moist tropics and across drier parts of Africa are likely to be utilised for more intensive agriculture in the near future (Ngumbi and Dindi, 2017). It has been estimated that already one fifth of the world's population live in or around savannas, and many of these areas are witnessing rapid increases in population growth (Furley, 2016).

Whilst some savanna soils may be amenable for conversion to agriculture, many tropical savanna soils have severe limitations. Unless these are overcome conversion to agriculture may not be sustainable, and could cause augmented desiccation, erosion, and nutrient loss. Even savanna soils that can support cultivation and livestock grazing are likely to experience loss of OM content, weakened nutrient cycling, and increasing CO<sub>2</sub> emissions, if converted. Savanna soils are also known to exhibit local variability, as exemplified by research in African savannas (Obalum *et al.*, 2017). Although scientists understand the variable land use potential of savanna lands, many national land use planners consider savanna lands as uniform in their use and value. For example, while analysing the potential of the Brazilian *cerrado* soils for land use conversion, Brannstrom *et al.*, (2008) amalgamate a wide range of savanna formations, summarising that the predominant soils are highly weathered and acidic Oxisols, whose high aluminium concentrations require fertilizers and lime for livestock and crop production. While accurate this fails to distinguish the significant local variation in the soils, such as the non-uniform textural profiles giving rise to Ultisols, deeper coarse-textured profiles developing Alfisols, or less developed Entisols on eroded rocky outcrops. Differences in topography and drainage also generate distinctive catena patterns (Furley 2000; 1996). Hence there is a considerable diversity of land use possibilities existing within *cerrado* soils. This emphasises the importance of understanding the nature and the variations in soil properties of savanna woodlands and grasslands, particularly for smallholder farmers with limited resources.

Savannas cover around 10% of the total land area in Belize and are therefore an important national ecosystem (Meerman, 2011). Similar small patches of savanna can be found throughout much of Central America and the Caribbean. Although Belizean savannas represent a small proportion of the

65 biome they illustrate how a fine-scale approach can address some of the global issues concerning  
66 development of savanna lands.

## 67       **2. Case study: savannas of Belize**

68 The savannas are an important but frequently disregarded natural resource. The land is viewed as  
69 being largely unsuited to farming other than low-density pastoralism and softwood extraction (King  
70 *et al.*, 1992; Haggis, 2013). Furthermore, although settlements and roads have been preferentially  
71 constructed on savanna land, most has remained commercially unused until recently. Whilst some  
72 tracts of savanna are designated as pine-forest reserves or are managed as nature reserves, the lack of  
73 a definite management policy in national land use legislation (Meerman, 2011) and a perception  
74 among local people that savannas are 'waste ground', has contributed to practices such as dumping,  
75 opportunistic harvesting and a lack of control of wildfires, resulting in widespread deterioration. In  
76 the last decade shrimp farming has encroached into savanna areas near the coast. As the population  
77 of Belize rises, marginal lands including the savannas are now starting to be developed for agriculture.  
78 Meerman and Cherrington (2005) warned in their general assessment of risks to land degradation in  
79 Belize that savanna soils were generally too acidic for conversion to agriculture. A later report by the  
80 Government of Belize's Department of Environment (2014) concluded that almost a third of the  
81 roughly 1 million acres of agricultural land in Belize now occurs on land classified as marginal or  
82 unsuitable for agriculture, and one third of all agricultural land occurred on acidic soils sensitive to  
83 land degradation. A nationwide GIS analysis of land use change by Cameron *et al.*, (2011) showed  
84 that more than 10% of the remaining savanna lands had been converted to other land uses in the past  
85 20 years of which agro-pasture and shrimp farming were the most frequent.

86 There are two principal savanna domains in Belize, which may be generalised as upland and lowland.  
87 The lowland savannas, which form the focus of this paper, are mostly located closer to sea level, with  
88 varied parent materials and some coastal influences such as saline spray and marine ingressions in  
89 low lying areas. The coastal plains are relatively flat and poorly drained, comprised of parent

90 materials made up from siliceous alluvium of various ages derived from the Maya Mountains and  
91 from Quaternary coastal marine deposits. The marked seasonality of the climate influences soil  
92 properties through wetting (temporary inundation) and drying (often intense) resulting in infertile  
93 soils that typically support savanna landscapes.

94 Despite the generally infertile nature of the soils, there are considerable variations in savanna soil  
95 properties, implying local differences in potential for agriculture and also possibilities for other types  
96 of land use being sustainable. Until now however, soil variability within savannas areas has been  
97 poorly understood. Assessments of savanna soils are now urgently required so that plans can be  
98 formulated before the pressure from the growing population results in unplanned and unsustainable  
99 development.

100 There have been very few studies dealing with savanna soils in Belize and none specifically  
101 concentrating on lowland formations. Further, the objectives of the present study differ from the  
102 comprehensive but broad scale national surveys conducted previously by the Land Resources  
103 Division of the ODA (King *et al.*, 1992). This study seeks to create a larger data set focused solely on  
104 the savanna soils and to use this information to assess whether there is any spatial variation in soil  
105 properties. It aims to establish if there are spatial soil groupings that could be used to make national  
106 land management policies more locally applicable.

### 107 **3. Methods**

#### 108 *3.1. Data assemblage*

109 To create a national savanna soils data set for Belize we sought an approach applicable internationally  
110 in other countries which also have limited resources for conducting extensive soil surveys. Firstly  
111 savanna data from pre-existing surveys were collated (Jenkin *et al.*, 1976; King *et al.*, 1986; Furley  
112 and Ratter, 1989; King *et al.*, 1989; King *et al.*, 1992; Furley *et al.*, 2001). This dataset was reduced  
113 and simplified to establish a subset of soil properties that were comparable across all the sites. New  
114 surveys and laboratory analysis of soil samples were conducted to increase coverage in areas where

the existing data were sparse or non-existent (Stuart *et al.*, 2012). Combining the historical data with the new surveys produced a total of 79 sites spread across the country (Figure 1). The full dataset may be accessed at <https://datashare.is.ed.ac.uk/handle/10283/3132>.

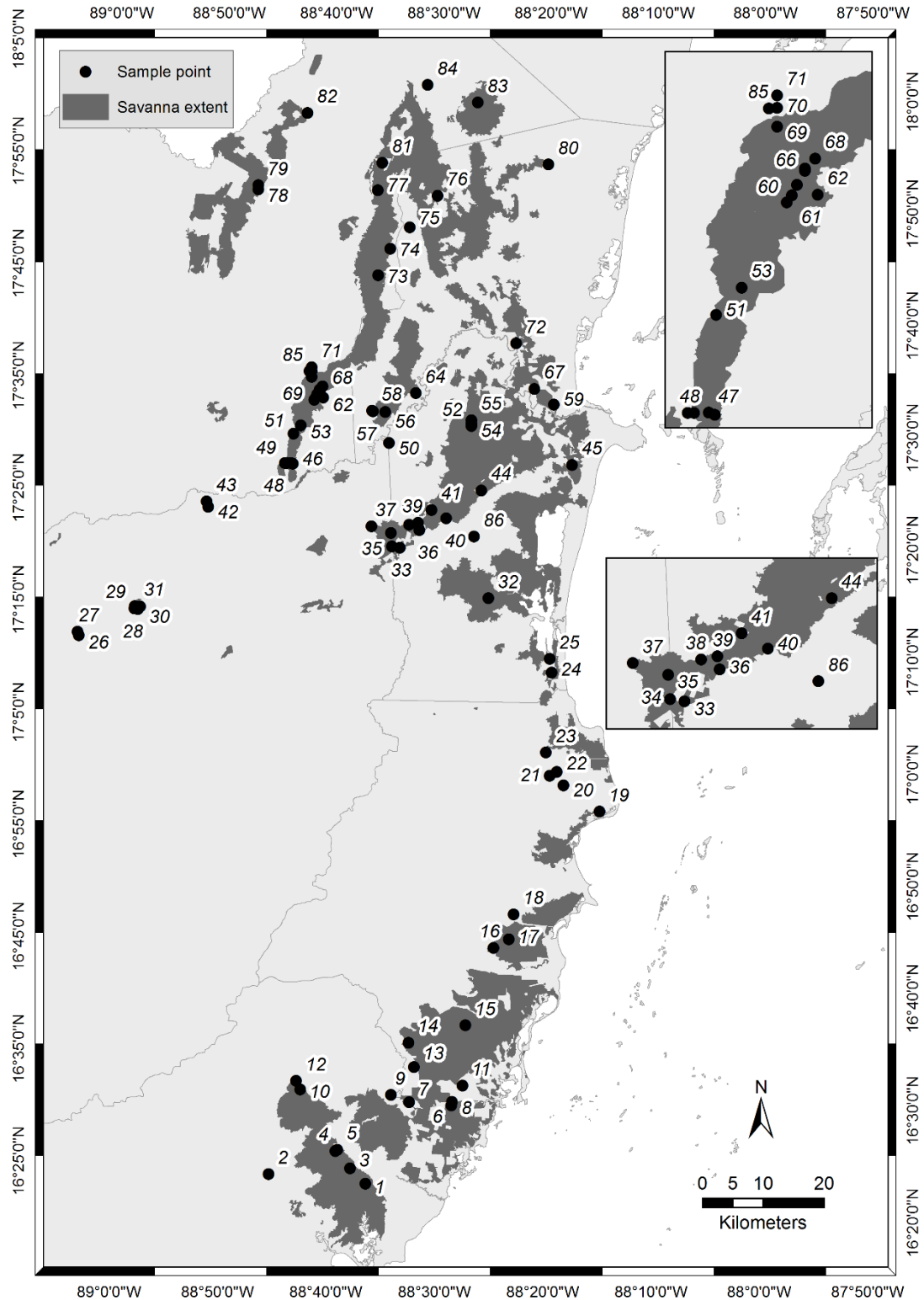


Figure 1: the distribution of soil sample sites used in this study (with site ID for reference and insets to magnify areas with high point density). Savanna extent is based on Meerman *et al.*'s. (2011) ecosystem survey and Cameron *et al.*'s (2011) remotely sensed data. Some sample locations predate the ecosystem surveys, therefore no longer occur on savanna vegetation.

120 All field samples were air-dried and then sieved (<2mm). The analyses followed standard procedures  
 121 so the data has international comparability. Field and laboratory methodology from the earlier surveys  
 122 i.e. ODA/NRI, are reported in King *et al.* (1992, Vol. II p289). Where possible identical methods of  
 123 analyses were used for the newly surveyed soils (Stuart *et al.*, 2012, Appendix 2), except that pH  
 124 measurements were only conducted in H<sub>2</sub>O, and a simplified particle size analysis was employed  
 125 (Kettler *et al.*, 2001). Profile descriptions included in the database provide further information about  
 126 all the sites.

Property	Weighting	Justification
Surface OM	5	Highest weight reflecting the importance of OM influencing soil fertility and moisture retention; most important in the top soil.
Subsurface Clay	4	Impedes drainage and limits rooting depth.
Surface Total N	4	Essential nutrient related to OM and indicator of surface conditions.
Surface pH	3	Influencing nutrient and cation availability.
Surface Clay	3	Influencing drainage, leaching and soil structure.
Surface Available P	3	Major limiting plant nutrient related to OM and particularly important at the surface and rooting zone.
Surface TEB	2	Influences pH and nutrient availability. Secondary impact on plant growth.
Subsurface pH	1.75	Influences nutrient availability and can reflect subsurface variations in parent material.
Subsurface Total N	1.25	Less of an influence on soil fertility and occurring in low concentrations in savanna soils.
Subsurface TEB	1.25	Less significant as there are lower nutrient concentrations.
Subsurface OM	1	Very low levels and limited impact.
Subsurface Available P	0.75	Generally very low concentrations.

127 Table 1: weights applied to each soil property in descending order, with justifications

### 128 3.3. Cluster analysis

129 Cluster analysis is a powerful data-mining tool as it classifies multivariate data into groups with  
 130 similar properties, thereby reducing data complexity and aiding interpretation. In the present study  
 131 cluster analysis was used to identify if there were any groupings of sites within the national dataset.  
 132 These were then mapped to examine if groups of soils with certain properties occurred in specific  
 133 parts of the country, and if this could be used to inform land assessment and management decisions.  
 134 Before analysis the soil dataset was reduced in complexity by selecting variables considered to be the



135 most significant when assessing land use and management. These were; clay percentage, pH, TEB,  
136 OM, total nitrogen, and available phosphorus, for both surface and subsurface horizons. As is usual  
137 with many clustering methods these soil properties were weighted to represent their relative  
138 importance in determining land suitability (Table 1). To allow comparison between soil properties  
139 measured on different scales, data for all properties were normalized into a 0-1 range using min-max  
140 normalization.

141 SPSS software (version 21) was used to perform cluster analysis in order to identify groups of sites  
142 that were similar in terms of these soil properties. Of the various alternative approaches to cluster  
143 analysis, such as hierarchical and model-based clustering, *k*-means clustering was selected as it  
144 permits individual sites to move between clusters during the iterations until an optimal result is  
145 achieved (Romesburg, 2004). As *k*-means clustering (MacQueen, 1967) partitions multivariate data  
146 into *k* clusters, an important parameter is the value of *k* (the number of groups generated). Different  
147 *k* values were tested and evaluated using the variance ratio criterion (VRC) (Calinski and Harabasz,  
148 1974). Partitioning into 3, 5, 8 or 10 groups generated acceptable VRC statistics. *k* = 5 groups were  
149 retained as this provided the best compromise between producing groups with statistically different  
150 properties and with some spatial pattern. For higher *k* values between-group differences were less  
151 clear and the spatial patterning less evident. A second key parameter are the sample sites chosen as  
152 the initial cluster centres around which the clusters are built. This choice can be influenced by the  
153 ordering of the input data. Therefore, to avoid the selection of less suitable initial cluster centres, the  
154 algorithm was re-run multiple times, each time with a random sorting of the input data. Results were  
155 evaluated using a one-way ANOVA in SPSS to generate the greatest difference between clusters. The  
156 final cluster analysis results were then validated using the C-Index internal validation method (Hubert  
157 and Schultz, 1976) using R software. For *k* = 5 the C-Index was 0.61, which we take to indicate an  
158 acceptable degree of intra-cluster similarity and inter-cluster difference for the purposes of an applied  
159 study such as this. For each of the 5 groups the mean and standard error for each soil property were  
160 extracted and plotted and the overall mean shown for comparison.

## 4. Results and discussion

### 4.1. Soil properties and spatial variations

The newly created database (n = 79) confirms that the properties of the Belizean soils (Table 2) are generally consistent with the global ranges for savanna soils, particularly those of moist neotropical savannas. They are typically acidic, nutrient-poor, and generally coarse-textured at the surface, with varying amounts of OM depending on drainage and vegetation cover. Most of the soils fall within the tropical categories of the USDA Ultisol and Entisol orders (Tropaquult and Tropofluvent), but some of the deeper sandy profiles are likely to be Spodosols (Tropohumod), or Alfisols (Albaqualf) developing in stretches with siliceous alluvium overlying calcareous parent materials (USDA, 2017). Inceptisols (Tropaquept) are found in seasonally waterlogged areas (Baillie *et al.*, 1993). However there are numerous transitions that reflect variations in the underlying parent materials and water balance, and many of the soil samples have compound profiles. These variants occur over heterogeneous scattered patches of savanna and examination of the site locations revealed how the soil properties sometimes changed markedly across relatively small distances.

	Property	Mean	S.E.	Range	Comment
Surface	Clay %	12.95	1.24	0 – 49	16% classed as type of clay soil <sup>1</sup>
	pH	5.45	0.07	4 - 7.1	84% are strongly or moderately acidic (i.e. $\leq 6$ ) <sup>1</sup>
	TEB(cmol/kg)	3.40	0.58	0 - 27.1	65% low i.e. $\leq 2$ cmol/kg <sup>2</sup>
	OM %	6.14	0.48	0.29 - 21.92	85% fall in very low–low range, with 56% in very low <sup>2</sup>
	Total N %	0.12	0.012	0 - 0.55	80% fall in low range ( $\leq 0.2\%$ ) <sup>2</sup>
	Avail P(ppm)	2.59	0.23	0 - 8.4	Only 14% above the critical level of 4ppm <sup>2</sup>
Subsurface	Clay %	34.05	2.2	0 – 73	67% type of clay soil, with 35% pure clay soils <sup>1</sup>
	pH	5.69	0.1	4.2 - 8.4	77% are strongly or moderately acidic (i.e. $\leq 6$ ) <sup>1</sup>
	TEB(cmol/kg)	6.67	1.4	0 - 65.1	62% low i.e. $\leq 2$ cmol/kg <sup>2</sup>
	OM %	0.97	0.16	0.3 - 7.98	97% fall in very low range <sup>2</sup>
	Total N %	0.029	0.003	0 - 0.1	All fall in low range ( $\leq 0.2\%$ ) <sup>2</sup>
	Avail P(ppm)	1.81	0.18	0 - 5.7	Only 9% above the critical level of 4ppm <sup>2</sup>

Table 2: key parameters of lowland Belizean savanna soils from this study. Reference sources are 1 - USDA (2017) and 2 - Landon (1984).

178 One unusual feature observed in many lowland sites in Belize is a low surface but high subsurface  
179 clay fraction with high bulk density. The mean surface clay content is 13% whereas the figure for the  
180 subsurface is 34% and over a third of the sites have high clay percentages (>40-50%). Where clay-  
181 rich subsoils are found over widespread areas of the lowland plain it has been suggested that  
182 eluviation of fine materials from upper soil horizons could account for the translocation and  
183 accumulation of clay sized particles in the B horizon (King *et al.*, 1992). However this is not a  
184 consistent pattern throughout the lowlands. Clay-rich soils also tend to occur in low-lying sections of  
185 nearly level or gently undulating landscapes where fine soil fractions have been washed laterally into  
186 depressions and shallow valleys, and dampness is often signalled by palmetto palm (*Acoellorraphe*  
187 *wrightii*). An alternative explanation is that the argillaceous substrate results partly from finer  
188 sediments of different geological provenance, overlain by more recent coarse alluvial deposits from  
189 the adjacent Maya Mountains or marine deposits. Consequently the parent materials can be multi-  
190 banded as recognised by King *et al.*, (1992). This proposal fits with the observed data, particularly  
191 along the southern coastal plains of Stann Creek and the Toldeo districts. In the future a more detailed  
192 analysis of clay minerals would help determine which process is dominant.

193 Soil pH is consistently acidic in both surface and subsurface horizons (mean = 5.4 and 5.7  
194 respectively). Nevertheless there are large variations with surface levels falling as low as 4 (Table 2).  
195 Lower soil pH is slightly more common in the south, which could occur because southern Belize  
196 receives higher rainfall than other parts of the country (Figure 2), and is therefore likely to experience  
197 greater leaching. Conversely in central and northern regions some subsurface soils have elevated pH  
198 with levels >8. A number of these sites appear to have been influenced by the proximity to the coast  
199 even where they are clearly located within broadly-defined savanna. For example, site 25 has a  
200 surface pH of nearly 5 but a TEB of 14 cmol/kg with nearly half contributed by exchangeable Na.  
201 More neutral or alkaline sites are also found where the weathered limestone bedrock (locally known  
202 as *sascab*) is closer to the surface and covered by only a thin layer of alluvial/palaeo-alluvial sands  
203 and gravels. At these sites the Ca, Mg and TEB levels are also elevated, as demonstrated by sites 37

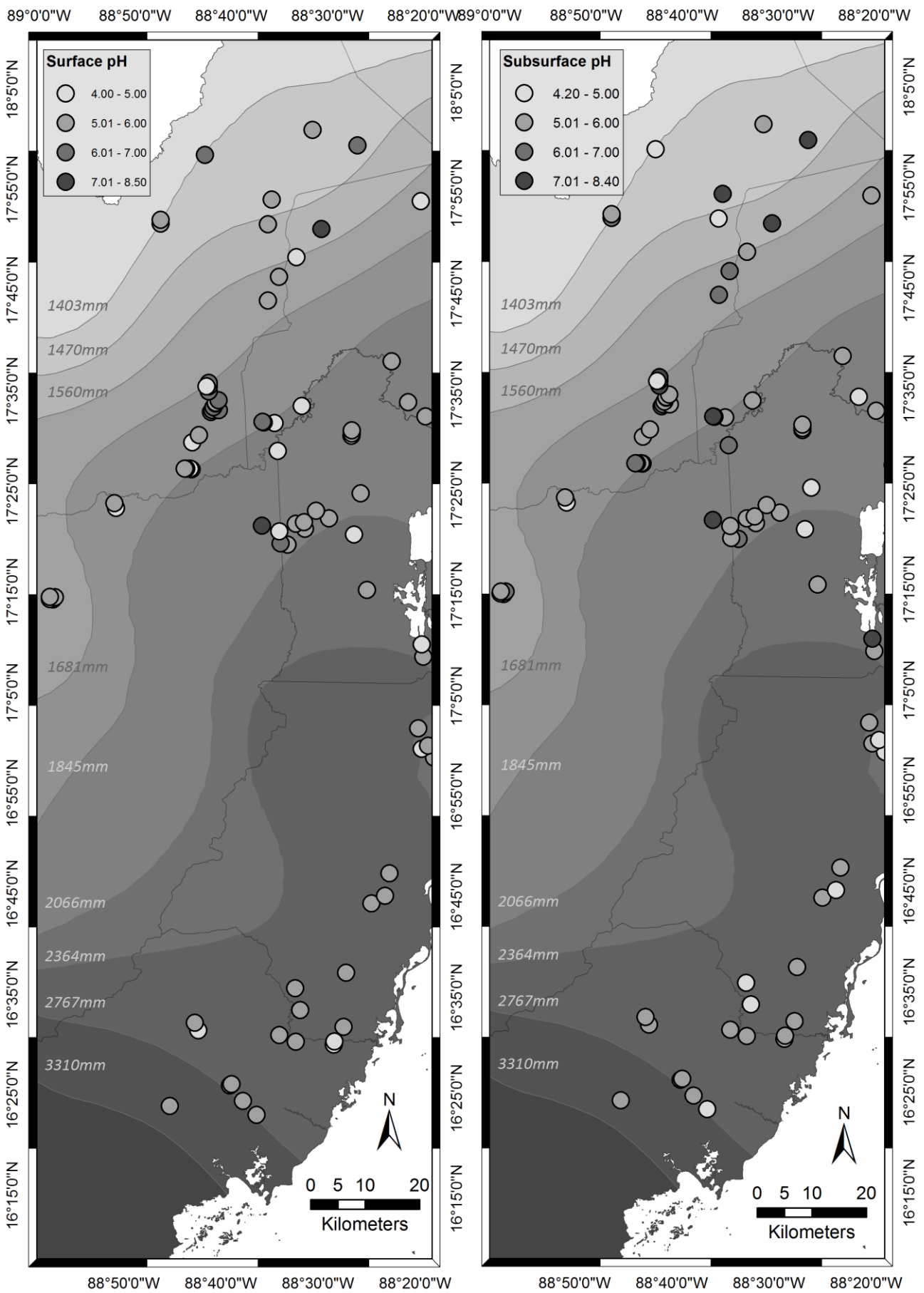


Figure 2: surface and subsurface pH of sample sites, with rainfall isohyets interpolated from 2013 annual rainfall data from Hyrdomet.gov.bz.

205 and 76 and possibly 83 (Figure 1). These sites have a subsurface pH levels of 8, 7.9 and 8.4  
206 respectively with subsurface TEB levels of 50, 27 and 30 cmol/kg. Furthermore Ca accounts for over  
207 90% of the TEB in these sites, specifically 99% at site 37, 93% at site 76, and 94% at site 83.

208 The OM, total N, and available P levels are as expected, i.e. higher in surface than subsurface soils  
209 and are generally low or very low (mean topsoil levels of 6.1%, 0.1% and 2.6% respectively). These  
210 low levels have possibly resulted from eluviation and leaching coupled with rapid decomposition  
211 (Ngatia *et al.*, 2014), and dehydration at different times of the year. Patches of more fertile surface  
212 soil with higher organic levels tend to be associated with the presence of denser vegetation, such as  
213 mixed savanna woodland. At these sites vegetation physically protects the soil and provides a constant  
214 input of organic material which retains moisture and mineralises nutrients. Additionally, high OM can  
215 occur in soils where the clay-rich subsurface has caused significant seasonal waterlogging, thereby  
216 reducing rates of decomposition. This is the case in site 62 where poor drainage from high subsurface  
217 clay (>60%) within a topographic depression, resulted in a dense growth of palmetto which  
218 contributed to the elevated topsoil organic content (8%) and slightly acidic pH value (6.0).

#### 219 4.2. Soil groupings

220 The cluster analysis of soil properties was used to produce 5 statistically distinct groups (Figures 3  
221 and 4). Comparison of inter-group soil properties and divergence from overall mean value for all the  
222 79 samples reveals a clear top-level split according to clay levels (Table 3). This divide possibly arises  
223 from differences in topography, geology and rainfall, as previously outlined.

224 The high clay groups (1, 2 and 5) have mostly developed on Pleistocene coastal deposits comprised  
225 of mudstones and other marine sediments, or older Tertiary (Toledo) beds over which there are varied  
226 layers of more recent alluvial or coastal deposits (Wright *et al.*, 1959). The differences between the  
227 groups reflect the proportions of fine fractions throughout the profile. Clay-rich subsoils are  
228 predominantly found in group 1 (n = 19), which is located in the central Belize river valley (e.g. sites  
229 56, 59, 40), and along the rivers of the southern coastal plains (e.g. sites 8, 11, 15) (Figure 3). This

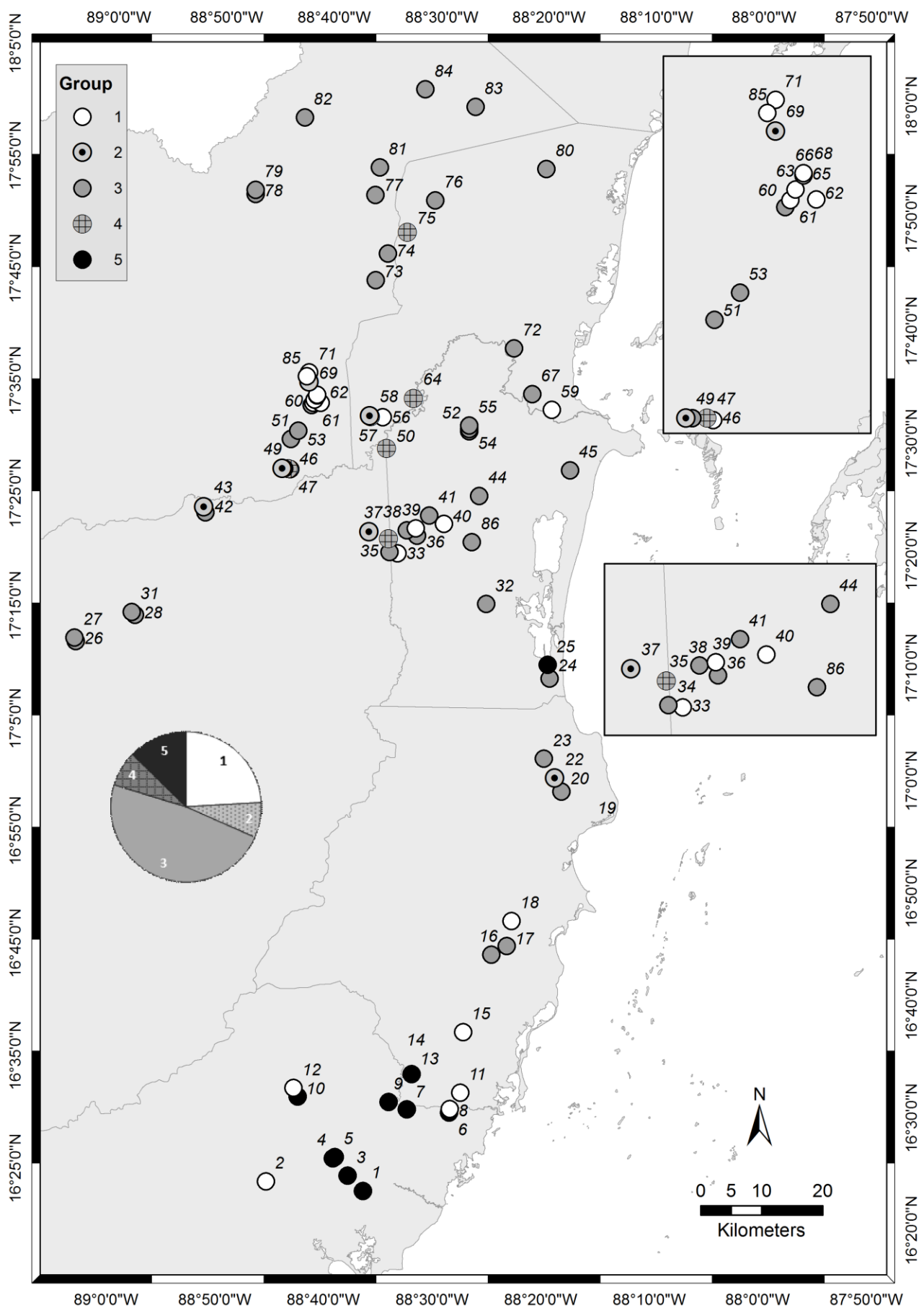


Figure 3: groups resulting from cluster analysis. The pie chart illustrates the proportion of sample points in each group.

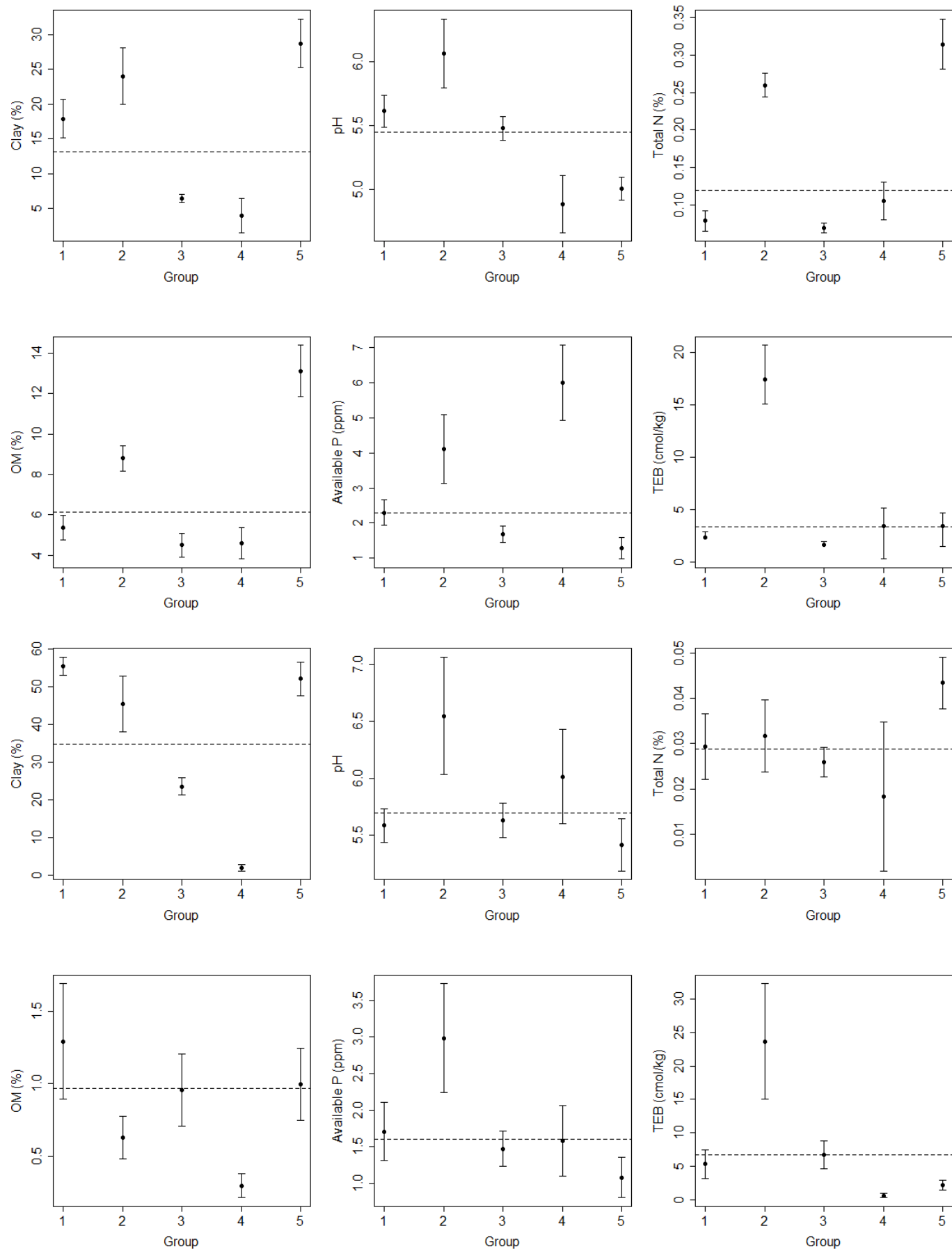


Figure 4: soil properties of each clustered group in the surface and subsurface horizons. Black dots represent the mean, and error bars are 1 standard error above and below the mean. The dashed line represents the mean value of the property for all sites.

group occurs predominantly within the Puletan Suite (King *et al.*, 1992, Table 4), with pale, coarse-textured, acidic, nutrient-poor, and well weathered surface horizons. However in places it is transitional to the Melinda Suite (ibid) where the soils are found in alluvial terraces and colluvial sites of river valleys (e.g. site 40). Subsequent soil evolution has resulted in impermeable clay-rich substrates (mean clay = 56%) beneath a coarser surface horizon (mean clay = 18%). The upper horizons are similar to the other savanna soils (such as the widespread group 3), being acidic with low nutrient levels and weakly organic. Group 2 is less typical of savanna soils due to its almost neutral pH (Figure 4). This small group of soils (n = 6) is concentrated in the central river valleys (Figure 3) and is derived from a thin cover of siliceous sands and gravels (alluvium) overlying calcareous parent materials. Where weathered limestone lies near the plant rooting zone the availability of cations (notably exchangeable Ca) supports a mixed vegetation (e.g. sites 37, 49, 58 and 69). In these areas a frequently sharp boundary occurs, and is represented at the surface by a clear transition between savanna vegetation above alluvial material and broad leafed or semi-deciduous forest overlying adjacent limestone parent material (Figure 5a). Unlike the other groups, group 5 is almost exclusively found in the southern coastal plains where it is intermixed with group 1 (Figure 3). Group 5 contains high surface clay levels (Figure 4), possibly a consequence of a layer of fan-like alluvium overlying the marine Toledo beds. Furthermore, group 5 has a more acidic pH than average, likely resulting from intensive leaching of base cations from the more prolonged rainfall in Southern Belize (Figure 2).

The groups with lower proportions of clay (3 and 4) are located in the central river valleys and northern Belizean plains where there is a variable cover of coarse-textured deposits. The parent materials represent various phases of siliceous alluvium eroded from igneous crystalline and sedimentary rocks of the Maya Mountains, possibly Late Tertiary-Pleistocene in age (King *et al.*, 1992; Wright *et al.*, 1959). This ancient detritus is believed to have been deposited as outwash over the undulating northern and central plains (Figure 5b) and is coincident with areas of characteristic savanna vegetation (Goodwin *et al.*, 2013). The deposits overlie weathered limestone at extremely



258 variable depths giving a range of soils supporting typical savanna to semi-evergreen forest, depending  
 259 upon the proximity of the calcareous parent materials to the surface (Figure 5a). Most of these soils  
 260 belong to the Puletan Suite (King *et al.*, 1992), which corresponds well with group 3 soils which have  
 261 the most widespread distribution (n = 38; locations and properties shown in Figures 3 and 4). The  
 262 occurrence of fine fractions in the subsurface with characteristic mottling is likely due to illuvial  
 263 accumulation. Group 3 sites are also found on some hillwash, residual and colluvial soils  
 264 predominantly derived from granitic parent materials, assigned by King *et al.*, (1992) as Stopper Suite  
 265 soils (e.g. sites 26-27 and 28-31). Group 4 comprises a smaller range of sites (n = 6), and are found  
 266 mainly within the Belize river valley or well-watered stream and lagoonal sites (i.e. at Crooked Tree,  
 267 site 75) (Figure 3). Group 4 profiles are found over older and recent alluvial sites in damp locations  
 268 often with palmetto as a co-dominant vegetation. Specifically, group 4 lacks the fine textured  
 269 substrate that is present in group 3 (Figure 4), but the sampling points are spread over a variety of  
 270 sites and it is difficult to pinpoint a consistent explanation. Another characteristic of group 4 is the  
 271 slightly higher surface P (Figure 4), which may be associated with a grassland vegetation cover and  
 272 in one instance (site 35) on herbaceous marsh. However few group 4 sites remain undisturbed, as  
 273 their more favourable soil properties means they have often already been exploited for agriculture  
 274 (e.g. sites 50 and 64). In contrast group 3 is more widespread and appears to be representative of clay-  
 275 poor and arguably more characteristic savanna soils. Since group 4 comprises a few scattered and  
 276 varied sites the two groups (3 and 4) are probably better considered together.

	Clay divide	Chemical divide	Group
Higher clay %	Very high in subsurface, medium in surface.	Average-low concentrations (both horizons)	1
	High in surface, medium in subsurface.	High pH, TEB & N/P; average-low OM (both horizons)	2
	Very high in both horizons	Low pH, TEB & P; average-high N & OM (both horizons)	5
Lower clay %	Average-low in both horizons	Average concentrations but slightly lower in surface compared with subsurface	3
	Very low in both horizons	Surface = low pH, high P, average OM, N, TEB; Subsurface = high pH, average P, low OM, N & TEB	4

277 *Table 3: key soil property differences between the resulting groups from cluster analysis. Note the comparison between*  
 278 *soil properties are relative, for actual values see figure 4.*

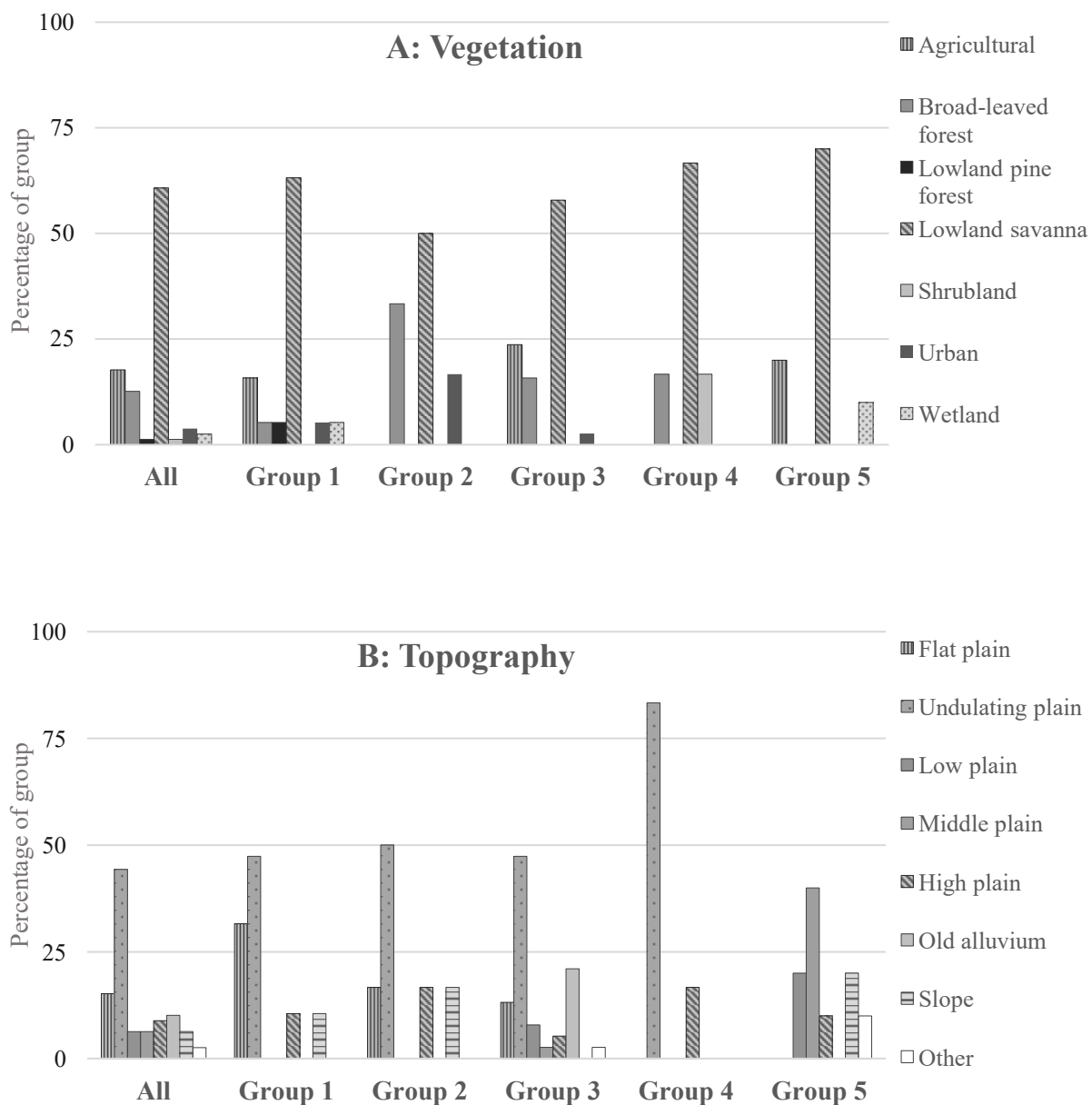


Figure 5: vegetation (A) and topography (B) characteristics for each group and all groups for comparison. The bars represent the percentage occurrence of the site characteristic in each group. Vegetation types were simplified from field notes, and topography descriptions were extracted from land system maps (King et al. 1992).

## 5. Implications for management

The groups identified by cluster analysis help simplify the complex variety of soils found over the savanna lowlands. Specifically, cluster analysis illustrates that some savanna soils may be suitable for agriculture in their present state, but these are scattered and of limited extent within the overall savanna mosaic. While most of the savanna soils are characterised by their acidic, infertile and coarse-textured surface horizons, there are several sites with more favourable properties that might sustain cultivation, particularly small-scale agriculture, or at least more intensive pastoralism. This inherent

287 variety in the potential of savanna soils was recognised in the work of the land resources assessment  
288 teams such as the Land Resource Development Centre, who indicated the need for detailed local and  
289 site investigation.

290 The most favourable group for agricultural development (group 4) is of limited extent within the  
291 present day distribution of savanna. It appears to be related to relatively recent alluvial and colluvial  
292 parent materials, along river valleys, seasonal streams, lacustrine margins or sites derived from  
293 granitic parent materials. The properties of group 4 fulfil the requirements for the best agricultural  
294 soils proposed by King *et al.*, (1993) in that they have developed in alluvium or colluvium similar to  
295 those classified as Melinda Suite, and are covered by grass-dominant savanna. Such soils provide a  
296 good rooting depth with adequate nutrient and water resources. Since these sites are amongst the most  
297 favourable and accessible locations in the country (Jenkin *et al.*, 1976; King *et al.*, 1993) many of  
298 these former savanna tracts (e.g. those in the Belize river valley) have been exploited.

299 By contrast, the sandy soils of the northern and central coastal plains are described as the ‘worst soils  
300 in the country’ for agricultural development (King *et al.*, 1993). Most of the soils classified as Puletan  
301 Suite fall into this category and are coincident with the group 3 soils which are found extensively.  
302 King *et al.*, (1993) suggest that the best and deepest of these soils could support tree crops like cashew,  
303 and where they are relatively freely drained could be utilised for the traditional uses of pine production  
304 and pasture. Nevertheless, any such land use would require nutrient supplements together with  
305 measures to counteract acidity and moisture variations, especially low soil moisture in the dry season.  
306 In this way chemical limitations in some of the group 3 soils could conceivably be ameliorated, as  
307 was achieved in the analogous *cerrado* and *llanos* soils in South America. Furthermore, the better  
308 drained soils of Group 3 in the southern coastal plains might support localised crops such as  
309 pineapple, cashew and coconut production, although sites with high subsurface clay will be least  
310 amenable to exploitation. The deeper soils characteristic of the transition to the Revenge Suite (mostly  
311 in the Northern coastal plains and defined as developing over mixed siliceous and calcareous parent  
312 materials) may also support coconut and pineapple production along with livestock, but much

Suite	Description	USDA equivalent <sup>1</sup>
Major suites:		
Puletan	The most widespread savanna group (>2/3 of land area). Developed over deposits of old (possibly Tertiary to mid-Pleistocene) siliceous alluvium. Derived from crystalline or meta-sedimentary rocks eroded from the Maya Mountains. Pale coarse-textured surface soils grading to mottled subsurface horizons which are frequently compact and impermeable. Variable depths and seasonally very wet (often flooded) or very dry (liable to drought). Leached, acidic and base-deficient soils with low levels of P and N.	- Ultisols ( <i>Tropodult</i> ; <i>Tropaquult</i> , <i>Albaquult</i> , <i>Paleaquult</i> ) - Spodosols ( <i>Tropohumod</i> ) if deeper sandy soil
Melinda	Derived from well to poorly drained river and floodplain alluvium, especially recent river basins draining to the coast from the southern Maya Mountains. Soil horizons exhibit banding reflecting their riverine history, frequently overlying old coastal deposits or alluvium. Significant nutrient deficiencies, but the better drained sites on more recent alluvium are capable of utilization for tree crops, pasture or (traditionally) milpa (shifting cultivation).	- Ultisols ( <i>Tropaquult</i> ) - Entisols ( <i>Tropofluvent</i> )
Stopper	Transitional soils developed in colluvial hillwash, and some residual soils derived from granitic parent materials. The latter have been largely cleared and typically utilised for citrus.	- Inceptisols ( <i>Dystropept</i> ) - Ultisols ( <i>Hapladult</i> )
Revenge	Moderately thick but variable depth of acidic siliceous surface soils overlying limestone. Marked vertical differences in soil properties reflecting the different provenances of the parent materials.	- Alfisols ( <i>Albaqualf</i> ) at the sandier end of the textural spectrum
Transitional Suites (occupying minor savanna areas):		
Yaxa	Well to imperfectly drained clay-rich soils developed over calcareous parent materials. Neutral to alkaline with sufficient base nutrients to support lowland forest and agriculture.	- Inceptisols ( <i>Eutropept</i> , <i>Tropaquept</i> ) - Alfisols ( <i>Rhodudalf</i> ) if deeper soils - Mollisols ( <i>Rendoll</i> ) at shallower sites
Jacinto	Mixture of Pleistocene coastal deposits, later alluvium over mudstones, calcareous sandstones, plus some conglomerates (Toledo Beds). Dark calcareous soils containing significant amounts of sand in the surface horizons with increasing levels of clay with depth. The soils have the greatest agricultural potential so have mostly been cleared of vegetation.	- Inceptisols ( <i>Eutropept</i> ) - Alfisols ( <i>Hapludalf</i> )
Tintal	Seasonally very poorly drained soils with varied textures and nutrient status; gleyed and often brackish.	- Inceptisols ( <i>Tropaquept</i> ) - Entisols ( <i>Fluvaquent</i> ) - grading to Histosols with increasing OM content
Guinea Grass	Dark calcareous soils with significant amounts of sand in the surface horizons becoming increasingly argillaceous with depth. Confined to northern Belize with very limited areas under savanna.	- Alfisols ( <i>Hapludalf</i> ) - Inceptisols ( <i>Eutropept</i> )
Ossory	Residual and hillwash soils derived from very varied metasediments from the Maya Mountain.	- Inceptisols ( <i>Dystropepts</i> ) - Ultisols ( <i>Hapladult</i> ) if deeper soils
Altun Ha	Medium and coarse-textured siliceous soils overlying limestones on the Northern Coastal Plain. Characteristically flinty with a neutral to slightly acidic pH.	- Inceptisols ( <i>Eutropept</i> ) - Alfisols ( <i>Hapludalf</i> )

Table 4: summary properties of the principal soil suites discussed in this paper with USDA equivalents (1 - USDA, 2017).

316 depends upon the compaction of the lower soil horizons and the degree of impermeability.

317 Many of the soils in groups 1, 2 and 5 have the potential for agriculture but are limited by the high  
318 clay levels in the B-horizon. The impermeable clay-rich substrate not only limits rooting depth but  
319 also impedes drainage causing perched water tables, seasonal or semi-permanent saturation, and a  
320 lack of aeration in the rooting zone. Where such soils are above the level of ground water the land  
321 would require a major engineering investment to reduce seasonal flooding in the wet season, and  
322 conversely in places to irrigate in the dry season. Therefore, capital intensive management techniques  
323 would be required to make these soils viable for agriculture, which is unlikely in the foreseeable  
324 future. However, although these solutions are uneconomic today future advances in technology may  
325 alter the economic balance meaning that these options for land management should be explored. If  
326 this occurred initial resources might best be focused on group 2 soils, which are clustered in the Belize  
327 River Valley and have slightly more favourable conditions (i.e. a neutral pH, less clay at depth, and  
328 higher TEB and N levels).

329 The savannas are under continuous and accelerating threat of development without a clear  
330 government policy towards their conservation or utilisation (Meerman, 2011). The scattered nature  
331 of the better savanna soils for agriculture may favour traditional smallholder farming in view of their  
332 small size and widespread distribution. The best soils offering possibilities for more commercial  
333 farming have mostly been utilised already. Management alternatives could be helped by information  
334 on the nature and potential development of soil resources along with consideration of their non-  
335 agricultural, forestry and biodiversity value. Several other potential uses for the lowland savannas  
336 have been investigated over the past decade. For instance, the conservation and tourism prospects are  
337 limited but significant. A number of plant species are specialists of pine savannas, including 17 of the  
338 41 country endemics (Goodwin *et al.*, 2013). Some animal species rely on savanna areas such as the  
339 critically endangered yellow headed parrot, whilst others such as the jaguar also utilise these more  
340 open landscapes. In addition, the savannas offer space that is welcomed by local inhabitants for  
341 recreation and as a community resource (Wells *et al.*, 2018). The Programme for Belize, a well-known

342 conservation NGO, occupies a major savanna area in the Northern plains and in the southern Toledo  
343 District, the Paynes Creek National Park is a significant biodiversity refuge, providing environmental  
344 regulation and forest resources in an area of limited agro-pastoral value.

## 345 **6. Conclusions**

346 The creation of this new data set confirms that the soil properties of the lowland savannas of Belize  
347 fall within the typical ranges of similar savannas worldwide, i.e. 84% of the samples are acidic,  
348 coarse-grained soils with low OM. However, a large number of sites have high proportions of  
349 impermeable subsurface clay. These are found in areas of level or gently undulating topography that  
350 result in seasonal or semi-permanently wet surface conditions. Another unusual aspect of this data set  
351 is the number of sites with high pH and TEB levels in the subsurface, which are located where more  
352 alkaline parent materials are found within the plant rooting zone.

353 The diversity of soil properties has been simplified by a cluster analysis, generating 5 soil groups that  
354 could support different future land management strategies. The most fertile soils are those of group  
355 4, which develop in relatively recent alluvium or colluvial parent materials, and will require careful  
356 nutrient management to maintain their productivity. The most widespread group (group 3) contains  
357 infertile soils, coarse-textured surface horizons, and is associated with more characteristic savanna  
358 vegetation. These soils could possibly be developed for agriculture with intensive fertilisation, as  
359 witnessed in the Brazilian *cerrados*. The groups exhibiting higher clay subsoils (groups 1, 2 and 5)  
360 are mainly found over the southern coastal plains where the heavier rainfall has led to greater leaching  
361 and nutrient-depleted topsoils. These soils could be used for forestry and aquaculture but have limited  
362 agricultural potential under present economic conditions. It is recommended that areas with extremely  
363 restricted drainage and severe nutrient limitations should not be developed, but could instead be  
364 managed for biodiversity conservation or recreation and tourism.

365 Our analysis of these soils and their variability across the country demonstrates the value of applying  
366 cluster analysis to finely-scaled data focusing on specific soil properties. This approach helps to

367 ensure that land use recommendations are sustainable and appropriate to soil capabilities, which is  
368 preferable to the previous national land use policy where all savanna lands were considered uniformly  
369 unsuitable for agriculture. Furthermore, the same methodology could be applied to other savanna  
370 areas where the data has a sparse spatial coverage or limited extent. Making more focused  
371 recommendations is likely to become more necessary as countries around the world are required to  
372 exploit their savanna soils more intensively as a consequence of population growth.

373 **Acknowledgements**

374 The authors would like to thank the support staff and field assistants from the Environmental Research  
375 Institute at the University of Belize for their help. Financial support was provided by the Carnegie  
376 Trust and the DEFRA Darwin Initiative Grant (#17022).

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